

X-ray Sources of Nanosecond Pulses Based on Semiconductor Opening Switch for CT

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Abstract. This study describes the development of prototype CT scanners with 2 different pulsed X-ray sources. X-ray sources used in this work have a semiconductor opening switch. It is used to generate high voltage pulses and provides pulse repetition frequency up to 5 kHz. The work uses two pulsed X-ray sources, which have different peak voltages and pulse energies. Tomographic sections and 3D images for test objects are obtained, the advantages of pulsed X-ray sources compared to continuous sources are discussed.

INTRODUCTION

Pulsed X-ray devices [1], in which high voltage pulses are formed due to a semiconductor opening switch (SOS) [2, 3], are promising. Unlike gas dischargers, SOS can create generators with a repetition frequency of high-voltage pulses to a few MHz [4] with a pulse duration of about 10^{-9} s and a peak power of 10^8 W. SOS-based pulsed X-ray sources have the following characteristics: the duration of X-ray pulses is about 30 ns, the pulse repetition frequency is up to 5 kHz, the maximum voltage is up to 500 kV, the pulse energy is from 0.2 to 5 J [5]. Typical design of the pulsed X-ray source is given in Fig. 1.

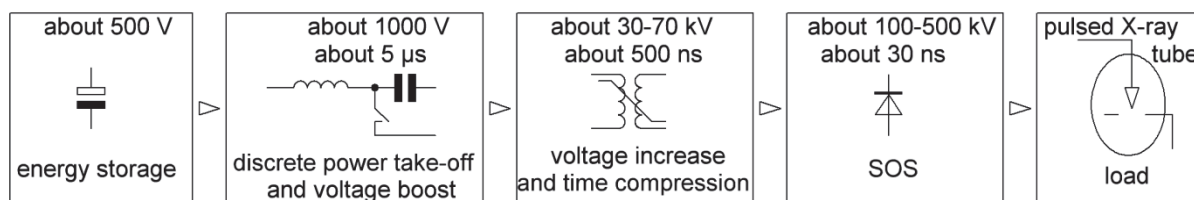


FIGURE 1. Typical design of the SOS-based high-voltage pulsed generator with an X-ray tube.

We believe that these pulsed X-ray sources can be promising for use in computed tomography (CT) and will reduce the disadvantages that are inherent in continuous devices. The CT method is a modern method of studying the internal structure of objects using X-rays. It has been rapidly developing starting from the end of the twentieth century, even though more than 100 years have passed since the day it was discovered [6]. This method of studying the object's internal structure is nondestructive, so it is widely used in different areas: medicine, defectoscopy, security control.

CT is of great importance in the study of internal organs of patients in medical research. Modern spiral tomographs use continuous X-ray sources and detector systems that operate at frequencies of 2–6 kHz. The X-ray tube and the detector system rotate at a high speed around the study object. During one exposure, the movement of the detector is about 2–6 mm, this leads to dynamic blurring. When using a pulsed X-ray source, instead of a continuous device, it is possible to obtain a better spatial resolution. The pulse source generates a powerful X-ray

flash with a duration of about 20 ns, the response on the detector will be clear; during this time, the movement of the detector is 10^4 times less, in contrast to the continuous device.

Another disadvantage is connected with a very high radiation dose to which the patient is exposed during one investigation [7, 8], it can be tens of millisievert. That is the reason why it is not advisable to use CT repeatedly or for children [9]. Traditionally, the reduction in the dose of radiation is achieved by improving the X-ray detectors (in particular, the use of efficient photon detectors) and the development of high-tech software to improve the image quality. However, we believe that additional radiation of patients is also caused by the use of continuous X-ray devices. Detectors operate in 2 modes: in one mode (t_a), they accumulate the signal, in the second mode (t_d), the received data is transferred to the computer and the detector is recovered (Fig. 2). At the time when the accumulated signal is transmitted from the detector, the patient is also under radiation but there is no useful signal. Perfect synchronization of the pulsed source and the detector allows to irradiate the object only when the detector is accumulating the signal, meanwhile when the data is being transmitted and the detector is recovering, the object is not irradiated. As the result the signal/noise ratio is increased considerably. This should lead to a reduction in patient radiation doses.

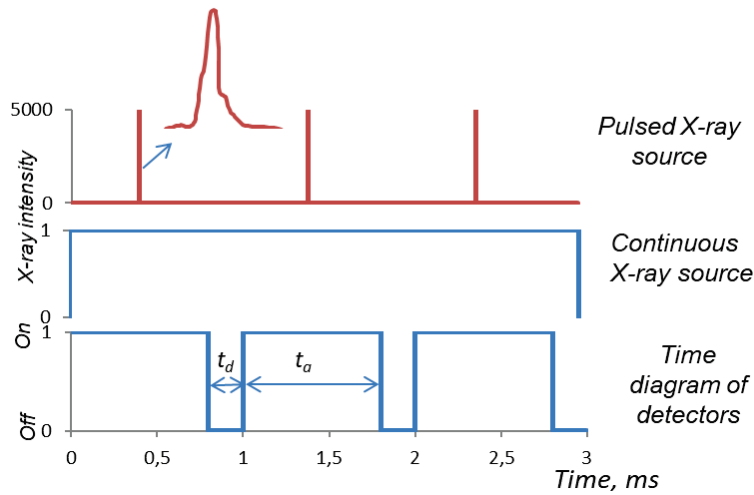


FIGURE 2. Operational diagrams of the pulsed x-ray source, a source of constant X-ray radiation, a receiving detector; t_a - signal accumulation time, t_d - dead time.

EXPERIMENT

A prototype CT with a pulsed X-ray source has been created. The schematic course of the experiment is shown in Fig. 3. The distance between the radiation source and the detector is 1 m. The pulsed X-ray tube consists of a comb-type metal-dielectric cathode and a tungsten-graphite anode. The tube has an effective focal spot diameter of 0.5 mm. The high-voltage generator has a completely solid-state element base, the final voltage pulse generator is SOS. The pulse generator is matched with the pulsed X-ray tube. The experiment used a medical flat-panel high-resolution detector CareStream DRX-1 based on amorphous silicon and gadolinium oxysulfide scintillator, pixel size is 139 microns, 14-bit analog-digital conversion. The test sample is secured on the stepper motor. This recording system operates only in a mode at which it is possible to obtain single pictures.

In the first experiment, a chicken is used as a test object. The object of study is located almost against the detector. This is done for simplification, when the object is located against the detector and at a great distance from the source, it is possible to obtain from the point source an image close to that obtained in parallel beams. It allows avoiding geometrical distortions on the X-ray image and simplify the process of tomographic sections reconstruction.

Stable generation of X-ray pulses is provided, the repetition frequency reaches 5 kHz. The amplitude of voltage pulses is 120 kV, the pulse current has values of the order of 180 A, the duration of the current pulse at half-height is 20 ns. The development of this source is described in [10, 11].

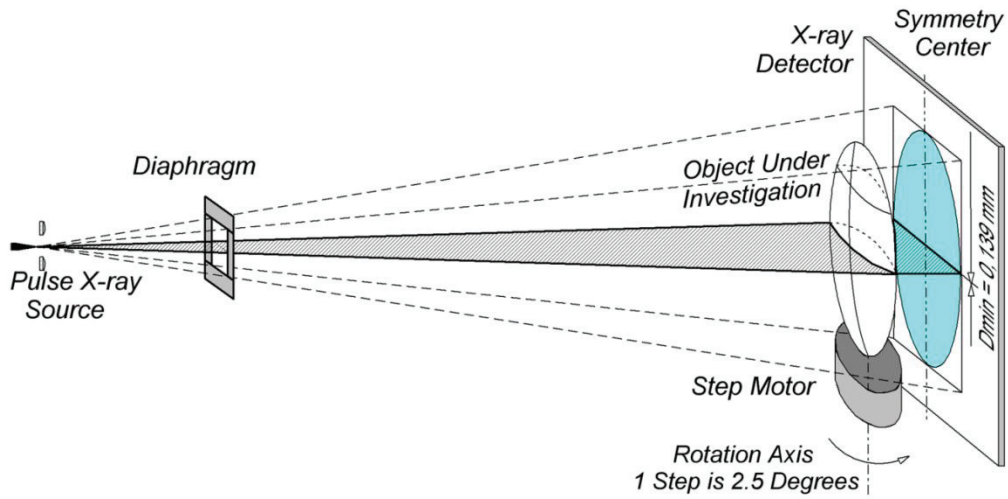


FIGURE 3. Experiment design.

73 projection images were obtained on the CareStream DRX-1 detector, the rotation angle has a discrete step and is equal to 2.5 degrees, the rotation is made from 0 to 180 degrees, one of the projections is shown in Fig. 4 (a).

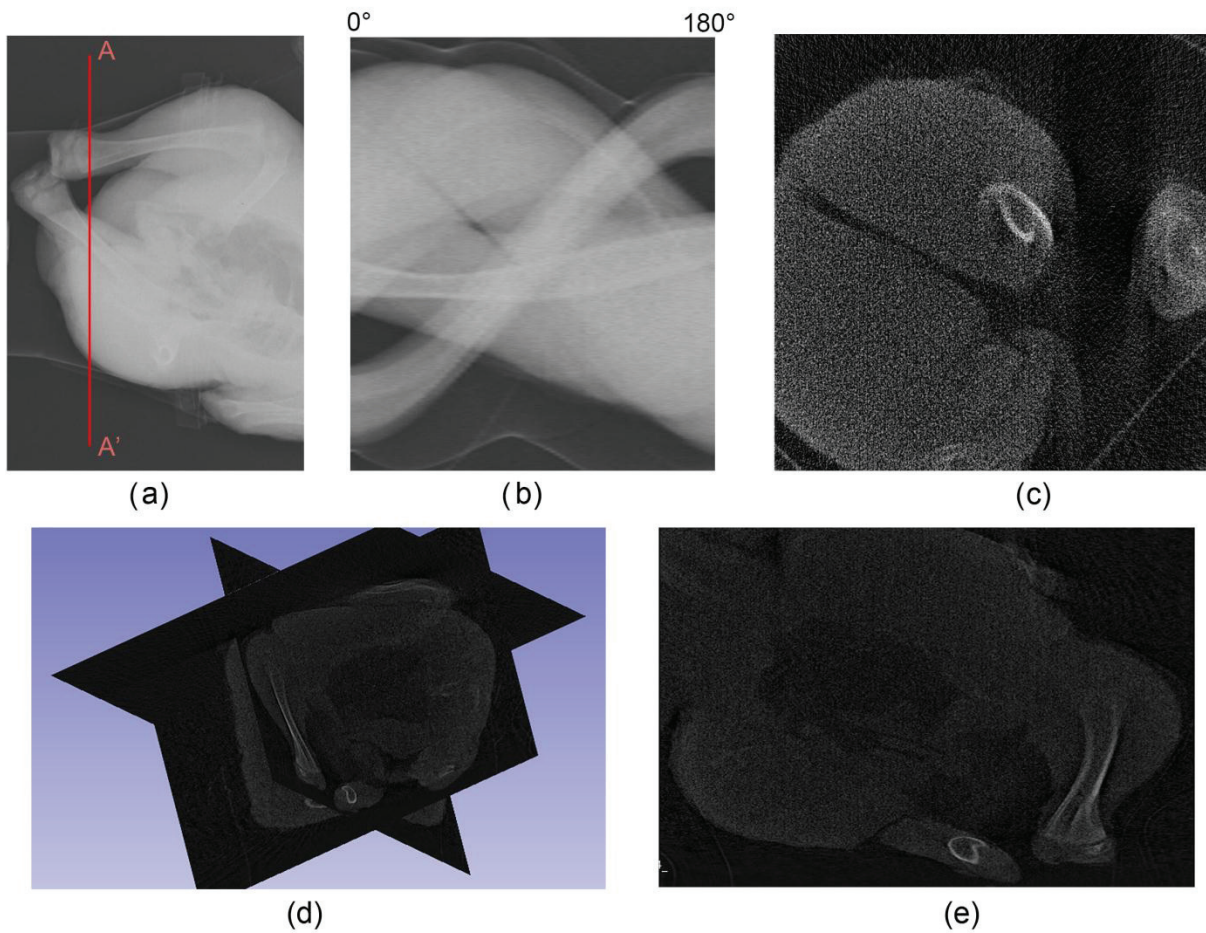


FIGURE 4. Projection image (a), synogram (b), tomographic section of the line AA' (c), 3D images (d, e) of the test object.

Each exposure is obtained with 20 X-ray flashes. Band AA' is marked on the projection, the width of the band is one detector pixel of 0.139 mm. We cut out such stripes from all projections. Every such stripe is a Radon transform. Next, a synogram was constructed from these stripes. In Fig. 4(b) you can see the synogram. The reconstruction of the tomographic section was performed using the inverse Radon transform (Fig. 4 (c)). We use the Python programming language and Iradon function for parallel beam projection. We automated the program to get many tomographic layers. For an object about 15 cm high, there are almost no geometric distortions, and the reconstruction of tomographic layers is performed correctly. 3D images of the test object are shown in Fig 4 (d, e).

The reconstructed tomographic image clearly shows muscle tissue and bone structure. The spatial resolution is about 0.2 mm. This is a fairly high resolution, which is often excessive in medical research.

A dosimeter (ionization chamber) is installed behind the diaphragm, the radiation dose of the object for this study for the entire object was 0.25 mSv. According to the results of this experiment, we can conclude that the operation of the pulsed X-ray source is stable, but achieving the described advantages requires a more powerful pulsed X-ray source, which would provide an image in one exposure for one X-ray flash.

For the second experiment, an X-ray source with a pulse voltage of 280 kV and a pulse energy of 3 J is developed. The duration of the X-ray flash at half-height is 40 ns, the repetition frequency reaches 2 kHz.

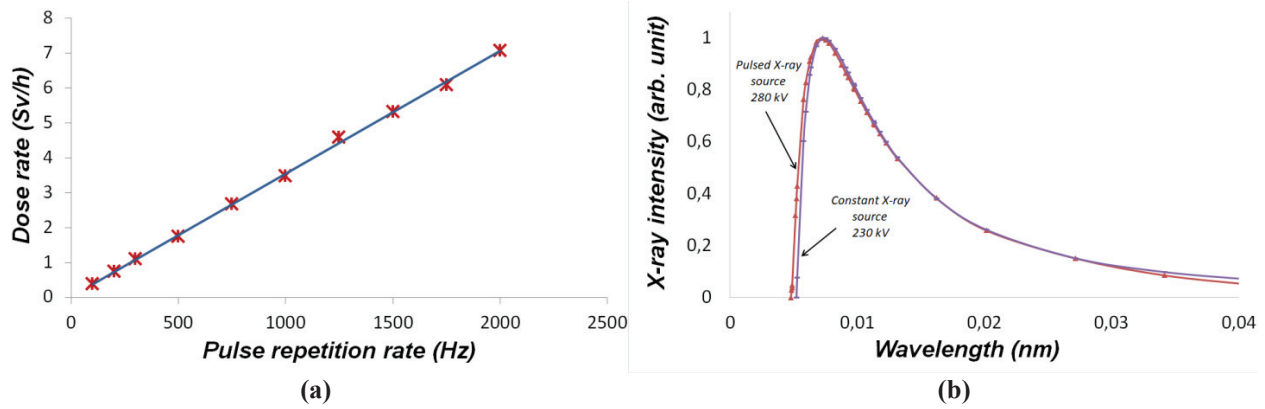


FIGURE 5. The radiation dose rate as a function of the pulse repetition rate (a), X-ray spectra (b).

Radiation dose rate of the developed source is shown in Fig. 5 (a). The distance from the radiation source is 1 m, the number of pulses per exposure is 100. AT1123 X-ray and gamma radiation dosimeter is used. We observe a linear increase in the dose rate when the pulse repetition rate increase. It means that the stability of a pulsed X-ray source does not depend on the pulse repetition rate. The average dose per pulse is about 1 μ Sv. We calculated a continuous X-ray spectrum using the Kramers formula. For pulsed X-ray radiation the change in voltage and current over the entire duration of the pulse is taken into account. The contribution of characteristic radiation is not considered. The calculation demonstrates that the radiation spectrum of a pulsed source with the peak voltage of 280 kV corresponds to the spectrum of a continuous radiation source with the voltage of 230 kV (Fig. 5 (b)).

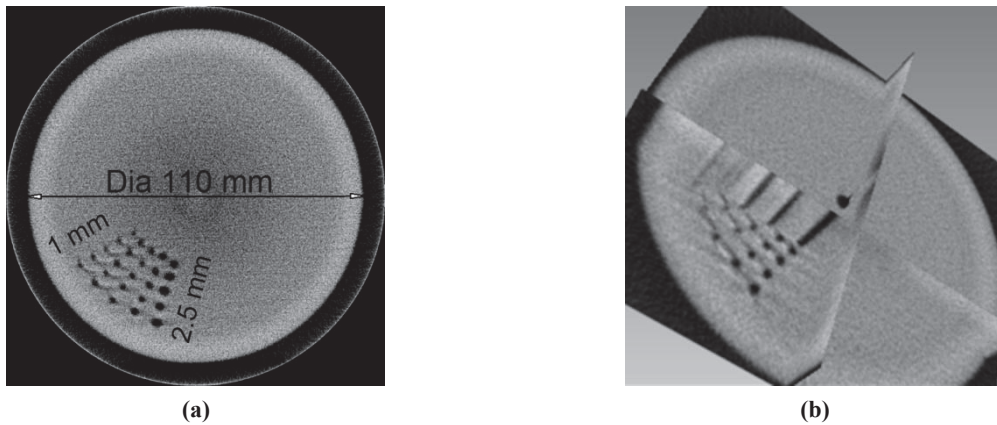


FIGURE 6. Tomographic slice (a) and 3D image (b) of the test object.

In this case, a phantom imitating the head of a child was used as an object of study. It is made of organic glass, and has groups of holes with different diameters. The discrete rotation pitch is 1.8 degrees, the rotation is made from 0 to 180 degrees. The center of the object is located at a distance of 70 cm from the source and 30 cm from the detector. One exposure is obtained per X-ray pulse. The reconstruction of the tomographic slice shown in Fig. 6 (a) was made in the MatLab software package. In this experiment, it is taken into account that the fan beam projection is used. First, the transition to a parallel beam projection is made, then the reconstruction is performed using the standard Iradon function. Geometric distortions are observed for the holes that are the most distant from the center; this is due to the fact that a large rotation step and insufficient number of exposures are selected. A 3D image of the test object is shown in Fig. 6 (b).

DISCUSSION AND CONCLUSIONS

This paper presents the development of prototype CT scanners with 2 different pulsed X-ray sources. The generator of high-voltage pulses of the source consists of solid-state elements, has an inductive energy storage and a SOS. Due to this design, the sources provide a repetition frequency of X-ray flashes up to several kHz with pulse durations of about 30 ns. The overall dimensions of pulsed X-ray sources are significantly smaller than the dimensions of devices with continuous radiation. The closest analogues of these devices are those in which the formation of the output pulse is provided by a gas discharger, but they operate at a pulse repetition frequency of about 10 Hz, which is not acceptable for CT.

In the first experiment we obtained 73 projection images, every exposition includes 20 X-ray pulses, so during the whole scanning there were 1460 pulses. Using the inverse radon transform 3D image of the test object was obtained. If the tube is operating continuously we can do it at the repetition rate of 1000 Hz in 1.46 s. It is impossible to increase the repetition rate, otherwise we observe anode destruction. We can increase the heat load of the anode by enlarging the focal point, it will reduce the resolution of the obtained images, but for many purposes such resolution will be enough. Another way of increasing power is using a rotating anode. It would make it possible to increase the heat power of pulsed tubes while preserving a small focal point.

In the second experiment, we used a more powerful pulsed X-ray source. One projection image is obtained per one X-ray flash. A 3D image was also obtained and all the holes are clearly visible.

These experiments showed a good prospect for the use of the developed pulsed X-ray sources for CT scanners. They have high radiation stability, good resolution, and a number of advantages over traditional continuous X-ray emitters.

Further work will be aimed at improving the heat removal from the anode because it imposes major restrictions on the use of these devices.

ACKNOWLEDGMENTS

The research is supported by the Russian Science Foundation (RSF), grant № 18-79-00020.

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